LUVOIR Telescope Temperature Considerations

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Introduction

The LUVOIR team would like to understand if operating the telescope below "room temperature," nominally 293 K, will help improve the 1.7 μm hard stop where thermal emission becomes an issue. This whitepaper discusses the issues with operating LUVOIR at temperatures below 293 K.

The difficulties of designing and validating a large space telescope that operates at temperatures below room temperature have been explored in great detail through the development of JWST, and primarily relate to three engineering challenges:

1. The need to fabricate and assemble a highly stable system that is guaranteed to function properly at cold temperatures.
2. The need to demonstrate the full end-to-end optical and mechanical performance of the telescope before launch.
3. The need to eliminate contamination prior to and during operations in order to achieve peak performance.

All of these challenges have engineering solutions, but the question is whether the science requires the cost and difficulty associated with those solutions.

Temperature vs. Thermal Background Radiation

The first question is what temperature a telescope needs to operate at to enable longer-wavelength science. To assess this, one must consider the temperature of everything in the optical chain (primary mirror, secondary mirror and struts, instrument optics and components, etc.). For simplicity, one can consider the radiance vs. wavelength of the telescope, including coatings, for varying temperatures. This assessment is shown below and was provided by Paul Lightsey of Ball Aerospace Technology Corporation. This analysis also uses Aluminum coatings which is the more pessimistic for IR emission, but the preferable coating for observations in the UV. However, gold and silver coatings, instead of aluminum, do not have a large impact to the story for telescope temperature and can be ignored at this level of fidelity.

Figure 1 plots the thermal emission at different telescope temperatures compared with the other limiting background flux, which is the Solar System zodiacal light. The case is a bounding case since it uses minimum Zodiacal emission ("Zodi") and 1.2× Zodi for comparison; when looking in the ecliptic, the zodiacal light is nearly 3× brighter. Fig. 1 shows that for faint-source observations to achieve the zodi background limit at 2.5 μm means that a telescope needs to be roughly 200 K. Also, a reduction of approximately 50 K from room temperature only buys about 0.3 μm near the Zodi limit. However, achieving a zodi-limited background flux is not necessary for bright-target applications such as stellar, planetary, or exoplanetary applications, and reductions in the thermal background at long wavelengths will still lead to improvements in sensitivity. We therefore address the impacts of decreasing the telescope temperature on the overall telescope engineering design.

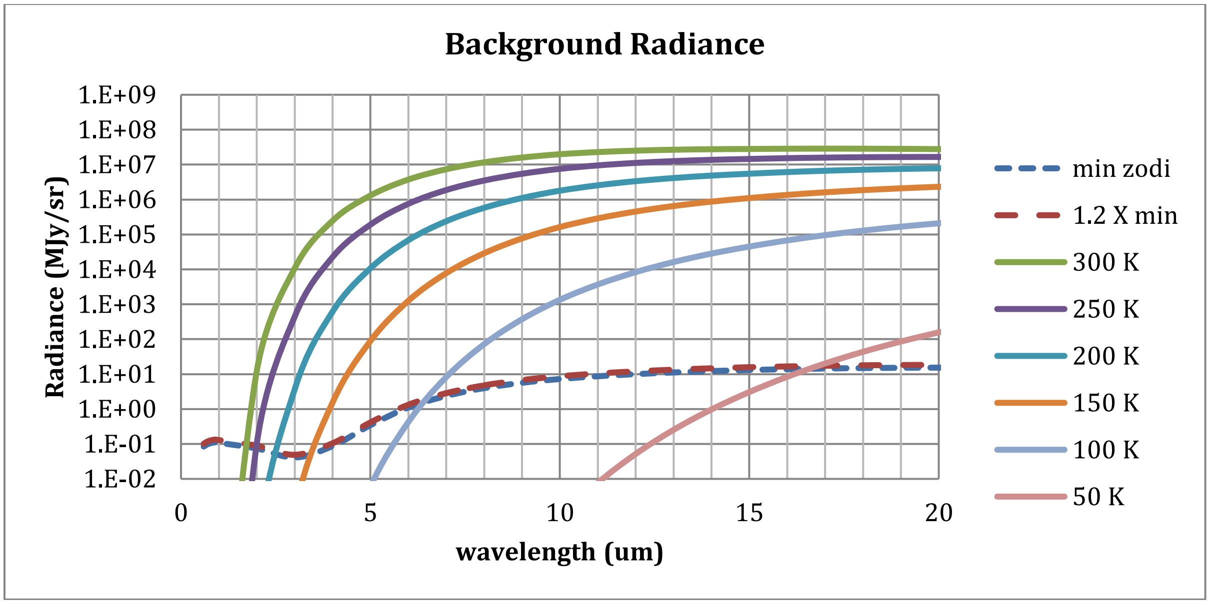

Figure 1: Radiance for different telescope temperatures

Impacts

There are a number of issues associated with operating a telescope at cold temperatures and the impacts vary depending on temperature and system architecture. A summary of these options and the level of complexity they add at different temperature regimes is shown in Figure 2 below. The temperatures chosen were natural break points which derive from physics. For example, we know that quartz crystal microbalance (QCM) monitors during JWST testing start to show large depositions at 260 K (a point where molecular deposition starts to happen), 200 K is above where water condenses (roughly 140 K to 170 K) but includes other molecular depositions, 140 K is where some materials have become CTE-stable (coefficient of thermal expansion), and 50 K is the JWST heritage where everything is frozen and Beryllium and JWST M55J laminates are stable.

Below is a summary of each of the considerations in the Figure 2. The topics are grouped by whether they are a significant factor in the trade space or not.

Figure 2: Temperature Cases vs. Complexity Considerations

Significant Factors:

Molecular Sticking vs UV Sensitivity – A critical factor in considering cold telescope is the fact that UV systems are extremely sensitive to even monolayers of UV absorbing molecules. The physics of this is related to absorption due to thickness of the contamination layer and the actual molecule type. As contaminants build up, the shortest wavelengths will see reductions first in throughput for layers as thing as a few Angstroms. For thicker films, quarter-wave effects will also come into play, but the first order phenomena is absorption.

To deal with molecular absorption, a key driver in UV systems is to carefully select, bake, and certify all materials to minimize molecular adherence and there is a long heritage of doing this at room temperature where the sticking coefficients in vacuum are low. Despite extensive work, epoxies, plasticizers used in cables, hydrocarbons from lubricants, and many other small residuals will exist and would stick depending on mirror temperatures. Water will also absorb and sticks in the 140-170 K range. For cryogenic optics or components, it is very possible that frequent bakeouts would be needed or even dual modes where baked off products are carefully managed (venting of cold fingers). There is not a heritage of doing this for UV systems because of the complexity.

An obvious question is whether any reduction in temperature can be acceptable. During JWST instrument testing, it was routinely found that at 243 K the QCM sensor would show significant depositions while at 258 K they did not. This suggests that 258 K is an approximate cutoff where molecules deposit (how many are UV absorbing will depend on the species). One possible strategy with cryogenic systems is to go above where water condenses in vacuum (170K) and is frozen in structures by going to 200K. However, other molecular species will have already deposited. For NUV, one could use a warm window to an instrument but at shorter wavelengths the availability of wide-band, highly-transmissive windows is limited.

Take-home Message: while it is not physically impossible to engineer solutions to achieve high UV sensitivities at cryogenic temperatures, it would add a high degree of complexity with many unknowns and with no true heritage.

Mirror Stability Varies with Temperature – Mirror stability is driven by the architecture of the mirror subsystem, which combines the material stability of the mirror substrate with local thermal controls designed to keep the temperature of the mirrors constant in the operational environment. However, different mirror materials have different stability characteristics at room temperature compared with lower temperatures, and the engineering solution for mirror segment control will be dominated by what materials are used and the thermal conditions of the segments. Exoplanet coronography with LUVOIR requires individual mirror segment stability of a few picometers RMS, which is a very significant technological challenge.

Material options for LUVOIR include ULE®, Zerodur®, and SiC for room temperature operation, and the same materials plus beryllium and silicon for colder temperatures. The current LUVOIR architecture is based on the high material stability of ULE® or Zerodur®, and low thermal and optical control authority, when operating at room temperature. To date, ULE® CTE and modeling at room temperature has been demonstrated to have the best uncontrolled thermal stability performance to meet the challenging stability requirements. ULE® at room temperature has heritage for high stability studies dating back to the TPF-C and Exo-C studies. A study conducted by Mike Eisenhower of SAO performed detailed modeling of ULE® at room temperature with CTE values measured from a real representative mirror boule. Eisenhower shows wavefront stability changes as small as 0.5 pm for a 1.2 meter flat-to-flat hexagonal mirror (approximately LUVOIR size) controlled with a 1 mK backplane heater plate (deemed feasible but challenging) and this is a key result for demonstrating the feasibility of LUVOIR.

Another consideration for LUVOIR mirrors is the degree of optical figure actuation that will be needed to meet stringent wavefront performance goals. ULE® mirrors can be equipped with mechanical actuators, to permit a certain degree of correctability. It remains to be shown how this will impact the thermal stability of the segment subsystem, however.

Other approaches are possible, with substrates with high thermal controllability, together with very precise thermal sensing and control, allowing use of stronger materials such as Silicon Carbide (SiC) and operation at a wider range of temperatures. SiC mirrors have been demonstrated with high levels of correctability by incorporating electrostrictive or piezoelectric actuators into the substrate structure. This gives SiC active mirrors the ability to operate at the required optical performance level both at 1G and 0G. It provides correctability for wavefront errors that can easily arise (and have often arisen in the past) during fabrication, test, assembly or launch. SiC mirrors have lower passive thermal stability at room temperature, but higher thermal controllability, than

ULE®. SiC at room temperature is a viable approach for LUVOIR mirrors provided that very precise thermal controls (to < 0.1 mK) are used. If temperatures below 150 K are desired, SiC stability improves to be better than conventional ULE®.

While additional details on mirror CTE and stability are controlled by International Trafficking and Arms Regulations (ITAR), the key point is that a ULE®-based, room-temperature approach appears to be feasible, while offering the least departure from traditional practice. While ULE® and Zerodur® can be tailored to cryogenic temperatures, picometer stability performance has not been assessed. At a minimum, going away from room temperature would risk the best possible stability performance that has been demonstrated and that builds on a large database and history including heritage back to the TPF-C design. While it is true other materials like SiC could have advantages for optical control, thermal control, mass efficiency, or dynamics stability, the need for these advantages is yet to be determined. Certainly dynamics can be addressed by making a stiff enough mirror through an increase in thickness for this segment size range (at larger diameters stiffness is a bigger concern).

Other materials like SiC, silicon, and beryllium have high CTE at room temperature but are thermally conductive and may offer stable solutions at colder temperatures and even Zerodur® or ULE® can be tailored for very low cryogenic CTE (e.g., at 150 K). While these solutions could offer stable solutions at cryogenic temperatures, more work would need to be done with substrate CTE measurements and modeling equivalent to the Eisenhower analysis. Note that while some mirror manufacturers will consider thermal conductivity when assessing stability, the LUVOIR architecture is not driven by thermal conductivity but rather is driven primarily by CTE performance and thermal inertia.

<u>Take-home Message:</u> The mirror materials for ultra-precise mirror stability with the best demonstrated performance and highest heritage are ULE® and Zerodur®, but both these materials are designed to operate at room temperature. Operating at a different temperature will necessitate a significant technology demonstration effort.

Dynamics/Temperature Dependent Damping – Thermal damping affects dynamics stability and the change in damping is as much as 10× from room temperature to 50 K. Damping follows curves for each type of material and small changes will have very small impacts. However, in general, warmer is better for dynamic damping. Less damping would impact WFE and line-of-sight dynamics.

Inclusion of electro-ceramic actuators in active SiC mirrors offers the possibility of passive or active damping of the mirror vibrations through simple shunt circuitry.

Coronagraph Temperature – To achieve longer wavelength performance for coronagraphy, not only does the telescope need to be cold, but so does the entire coronagraph instrument including the deformable mirrors, Lyot stops, occulting mask, and optical train. All of these coronagraph technologies have a long technological history for picometer stability and high contrast at room temperature. While some actuators can work at colder temperatures, a whole technology development program would be needed including the picometer stability performance of such systems at colder temperatures. This essentially would restart the coronagraph technology effort and would prevent using WFIRST heritage directly. Of course, this is only applicable for coronographic measurements, and would not apply to other infrared instruments.

Cryo Polishing – The wavefront budget for LUVOIR is surprisingly tight for a 500 nm diffraction-limited wavefront performance. A single primary mirror segment needs to have 10 nm RMS wavefront (5 nm RMS surface) which is roughly 4× tighter than what was done on JWST. This includes gravity backout and metrology uncertainties and is already considered a very challenging requirement at room temperature (especially gravity effects and the need to match radius of curvature). Due to CTE effects, mirrors distort as they go cold by many nanometers so cold optics will need to be tested at temperature and go through a cryo-polishing iteration, adding metrology uncertainty, and requiring significantly more time. A single cryogenic test for a JWST mirror would take anywhere from 3-6 months when you consider all of the logistics and pre- and post-integration and testing needed. Testing many segments could add one or more years to the critical path of the telescope.

Material Strength / Mismatch – Any material mismatch (mirror to mounts, mounts to flexures, etc.) will have temperature induced stresses. This can impact strength margins and every material mismatch will need to be analyzed and likely tested at temperature (pull tests). Also, other material properties like stiffness can vary with temperature and material testing may be needed. These issues required complex flexures to be included on JWST that required a significant amount of time and testing in the design phase and additional time in the production phase. Just the additional time to design the very complex flexures for JWST likely added more than a year to the design phase of the mirror segments.

Cryo Alignments – it is highly desirable to be able to align the system at room temperature and know that it will be aligned at operating temperature. Otherwise accurate models will be needed to predict alignment changes, compensated, and verified at temperature. A way to deal with this is to use cryo actuators to compensate for misalignments as done on JWST segments, but this can introduce additional requirements and complexities.

Cold Survival Considerations and Epoxy and Bond Considerations – An important issue is that acrylics used to hold multi-layer insulation (MLI) and epoxies used to bond nearly everything have glass transition temperatures that can impact their strength or cause other problems like contamination. These are typically in the 240 – 220 K range. To deal with this, cryo strength and contamination testing is needed. In addition, every bond and joint will not only need to be analyzed for room temperature launch loads, but also for cryo strength margins. Likely this means considerable testing for cryo material strength at the proposed temperature, which was a cause of cost and complexity on JWST.

Heater Power – The biggest engineering advantage for cold operation of the telescope is the fact that this would reduce the needed heater power at L2. Our studies have indicated a well-insulated mirror would need about 20-30 Watts to maintain room temperature at L2 so total power just for mirrors on a 12 meter telescope will be approximately 1.5 kW and the backplane could require as much or more (still under study). This is a large power consumption but not undoable (for reference, HST uses 2800 Watts). In addition, strides are being made in solar array efficiency and it may be that the mass and cost of the arrays in this timeframe are no larger than other large observatories.

Shock – Cryo shock is an important consideration because at cold temperatures the shocks are not absorbed as well. For JWST, shock has played a key role in driving the launch restraint mechanism selection which has been challenging, and drove extensive cryo shock testing. With this experience, the issue could be reduced but will still be a complexity driver depending on how cold an operating temperature is chosen.

Less significant factors:

Composite Stability and Complexity – For totally passive systems, backplane CTE for stability is a similar issue to that for mirrors. However, one not only needs to consider stability but also cryo stress and cryo distortion of the backplane itself. On JWST, cryogenic temperatures drove the backplane schedule in a large way. Every joint type and bond had to be assessed for cool-down stresses (in addition to launch loads). Both stability and thermal distortion had to be modeled in the design and then verified through cryogenic testing. The CTE of every tube needed to be measured and statistical studies done to assess backplane stability. A whole technology was needed to develop the 50-K-stable backplane material. Since there is a huge database and experience with room temperature composites, going cold and especially a temperature that is not room temperature or 50 K could require extensive material testing and possibly even new laminate design.

One way to mitigate backplane stability (and stability only) is to use edge sensors or laser metrology in a loop with a segmented DM to mitigate segment jitter. Segment motions due to thermal changes can be controlled with feedback to segment actuators. Our goal is to not need edge sensors but we are making this a high priority to develop. If a metrology solution is developed, thermal stability will prove less important than dynamic stability, which would favor a SiC backplane solution. For this reason, composite stability and complexity may not be a major driver in this trade although having the possibility of a low CTE composite option at room temperature is desirable to maintain. In addition, the likely edge sensor technologies have a room temperature heritage (capacitive and laser metrology technologies) so going cold might complicate this problem.

Cryo Thermal Testing – Anything cold will need to be tested at cold temperatures which can take extra time and add complexity. This includes thermal balance testing and verification of all electrical connections where impedances and phase vary with temperature.

System Optical Testing – In general it is important to test an optical system at operating temperature. This is for system WFE, alignment, wavefront sensing and control, etc. So if the telescope is cold, room temperature optical testing will likely not be sufficient. The system testing of JWST was a major cost and complexity driver.

Cryo Lubricants – At some temperature, typical warm lubricants will need to be replaced. This can also mean bearings need to be revisited. While cryo lubricants do exist, cryo actuators are more complex and generally more expensive.

Demonstrated Mid-frequency and Roughness – UV and high contrast systems require very tight controls on both mid-frequency wavefront and surface roughness errors. To this end, glass mirrors like ULE®, Fused Silica, and Zerodur® have been used on most UV and EUV telescopes including Hubble and Fuse. Polishing of Si-clad or chemical-vapor deposition (CVD)-clad SiC can also achieve good surface roughness, although CVD SiC is harder to polish. Another solution for SiC is to embed actuators for higher control authority.